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Advanced Penetrator Materials

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Abstract	
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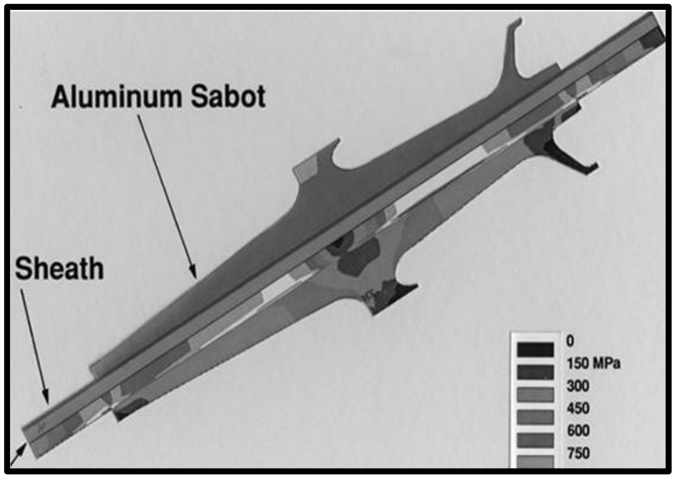
OUTLINE

- Background: Relationships between Properties and Performance of High-Density Materials
  - the adiabatic shear failure of DU
  - general approaches to alloy development
- Uranium (U-V-X) Alloys
- Alternative Matrix (adiabatic shearing) Tungsten Composites
- Amorphous and Nanocrystalline Alloys
- Severe Deformation Processed WHAs
- Jacketed Penetrators
- Conclusions

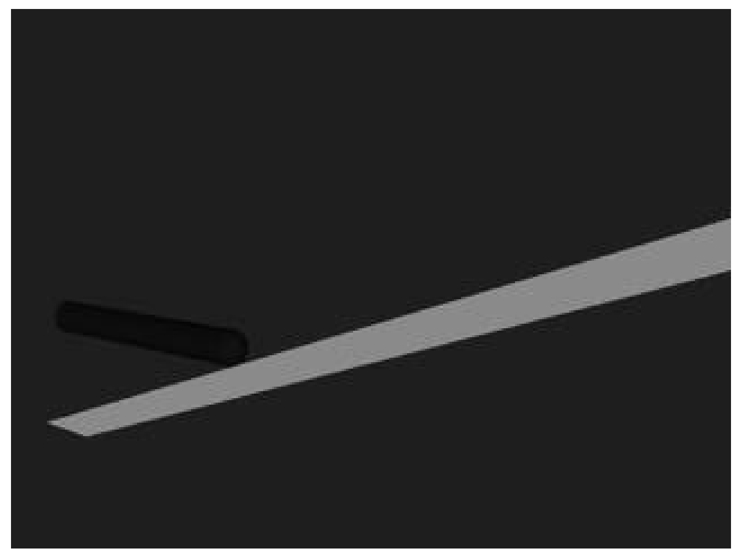
Properties vs. Performance Relationships/Requirements



- Engineering properties: strength and toughness.
  - Allow more efficient sabots/projectiles.
  - Resist complex armors.
  - Soft-launched projectiles expand options.

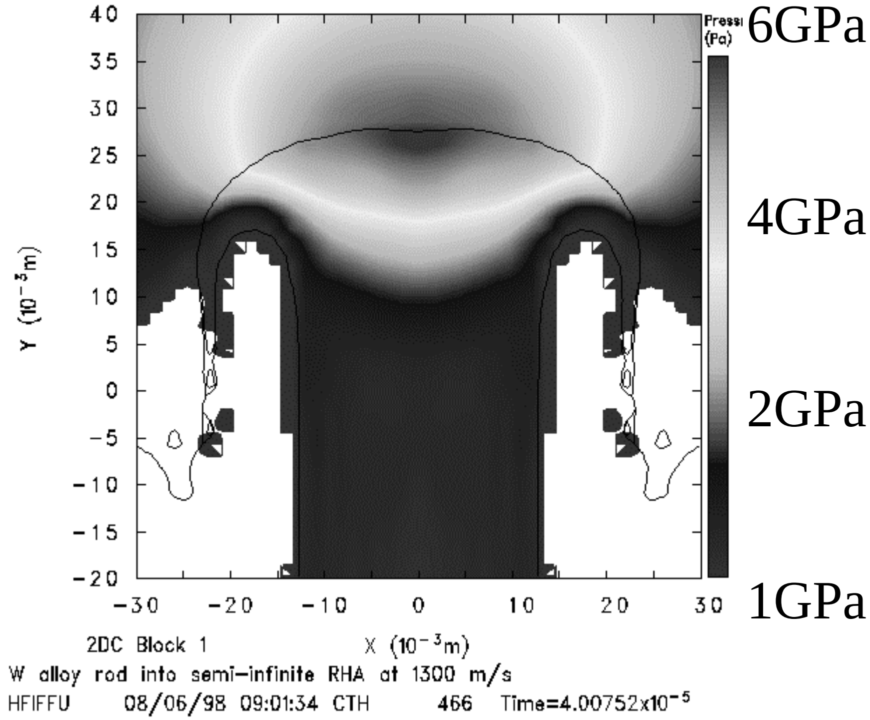
•High-rate, high pressure, deformation.

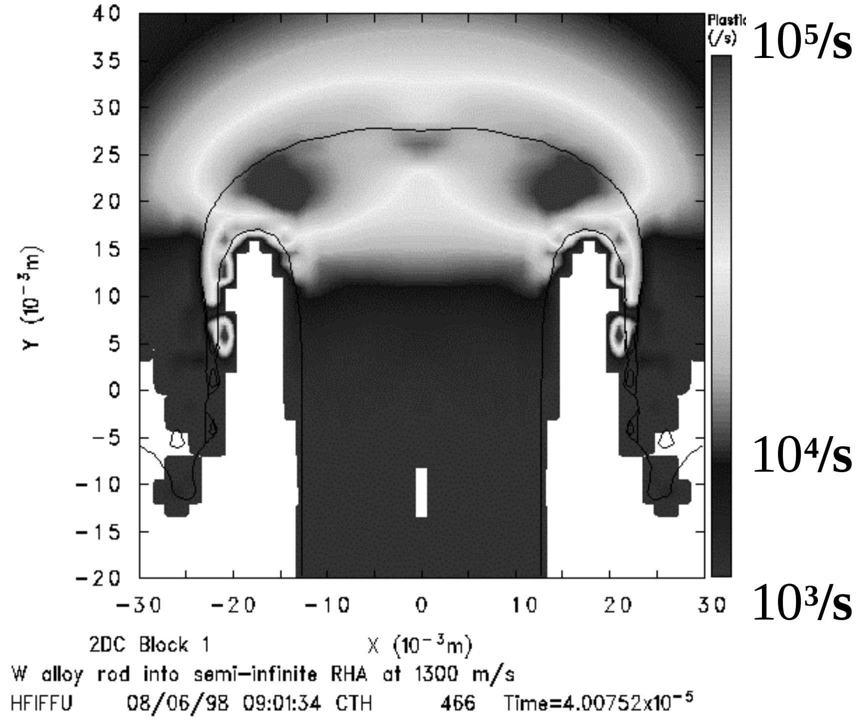
- Controls efficiency during deep penetration.



At the present time, Depleted Uranium alloys provide the best overall combination of structural and high-rate properties.

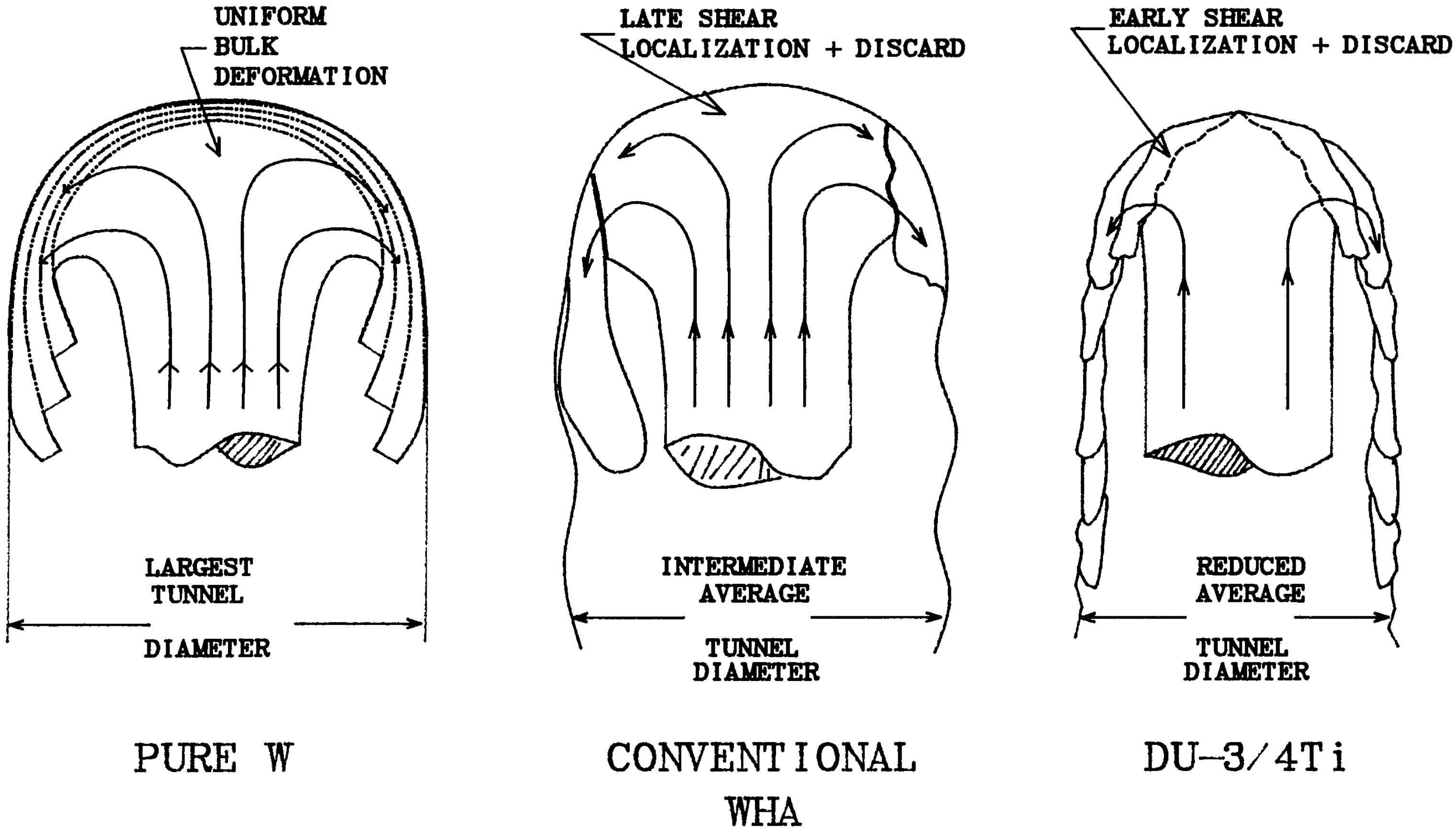
Pressure & Strain Rate Distributions During Deep Penetration





Strain-hardening and thermal-softening mechanisms compete during the high rate (adiabatic) deformation.

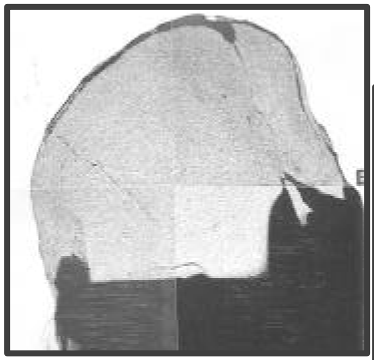
Flow/Failure of High-Density Penetrator Materials



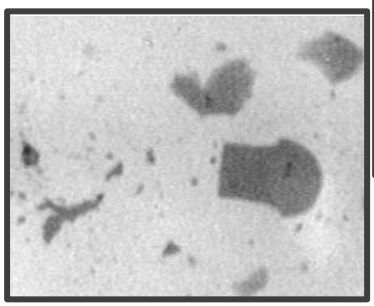
DU failure by adiabatic shear. This reduces the size of penetrator head, burrows narrower & deeper cavity.

Flow and Failure of High Density Penetrator Materials

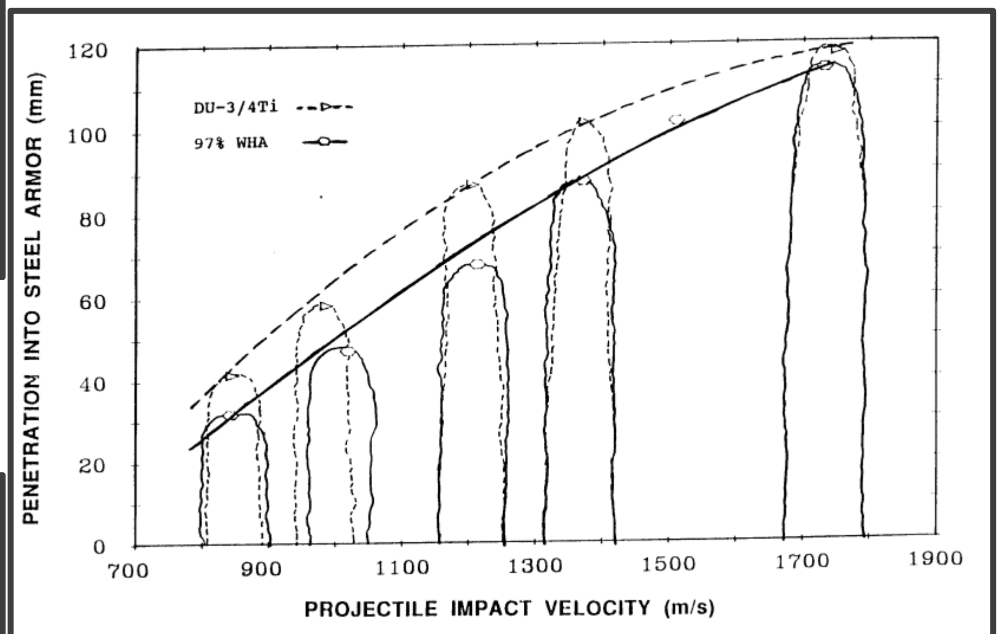
TUNGSTEN HEAVY ALLOY



- **WIDER CHANNEL**
- **MUSHROOM NOSE**
- **LESS DEPTH**

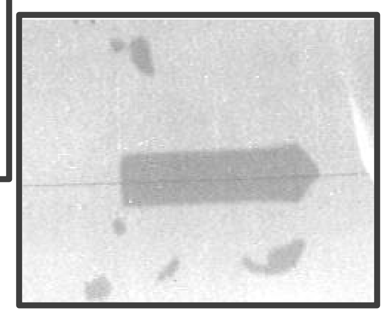


W-Ni-Fe



U-3/4 Ti ALLOY

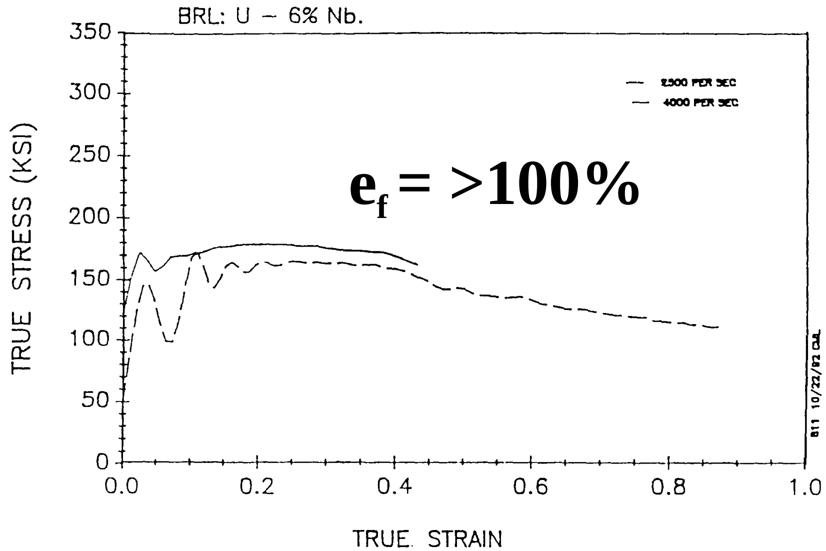
- **REMAINS SHARP**
- **NARROW CHANNEL**
- **DEEPER CAVITY**

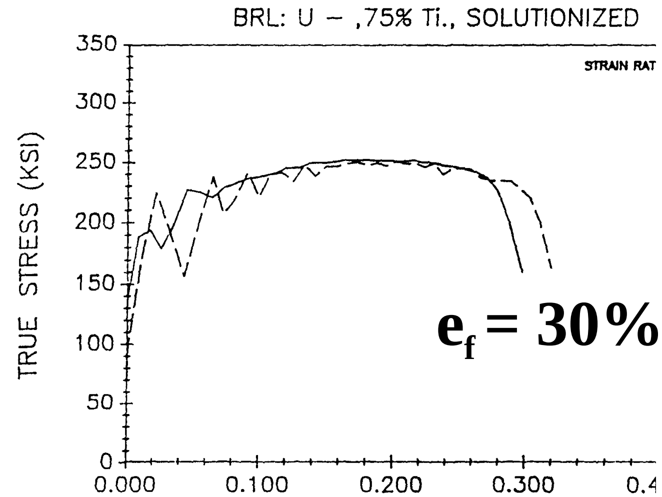


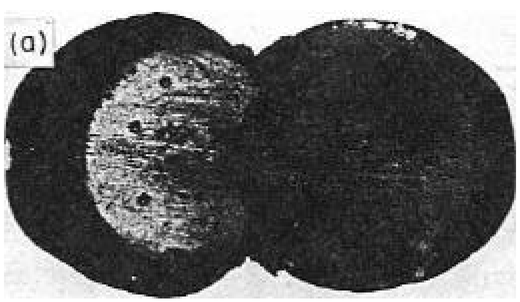
U-8Mo ALLOY

Dynamic (SHB) CompressionTests

(strain to adiabatic shear failure)





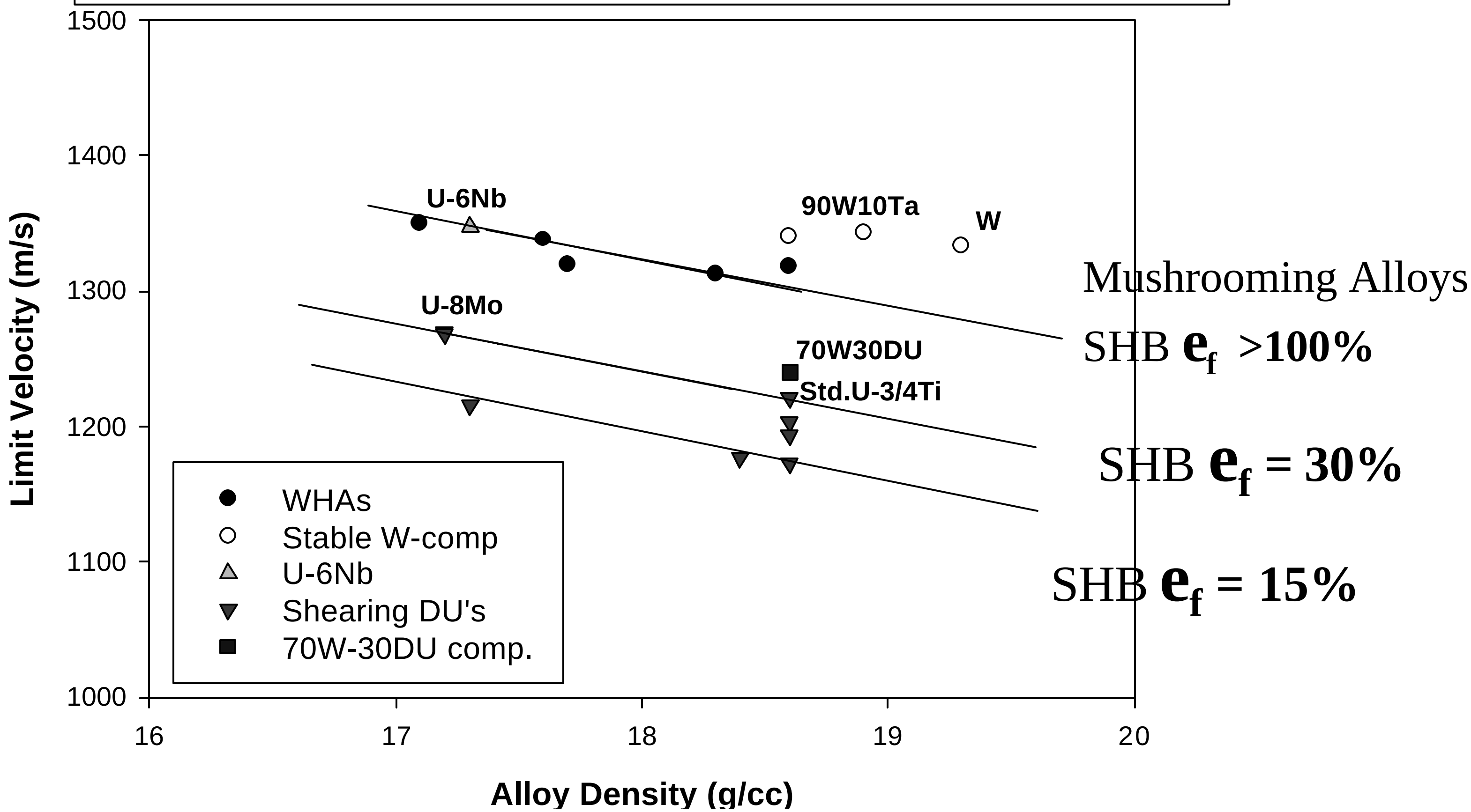


U-3/4Ti specimen cleaved by shear band

Dynamic compression experiments provide a means for assessing material failure behavior at high loading rates.

Comparison of RHA Steel Perforation Capabilities

¼-scale tests, 65g L/D=15 rods vs. 76.2mm RHA

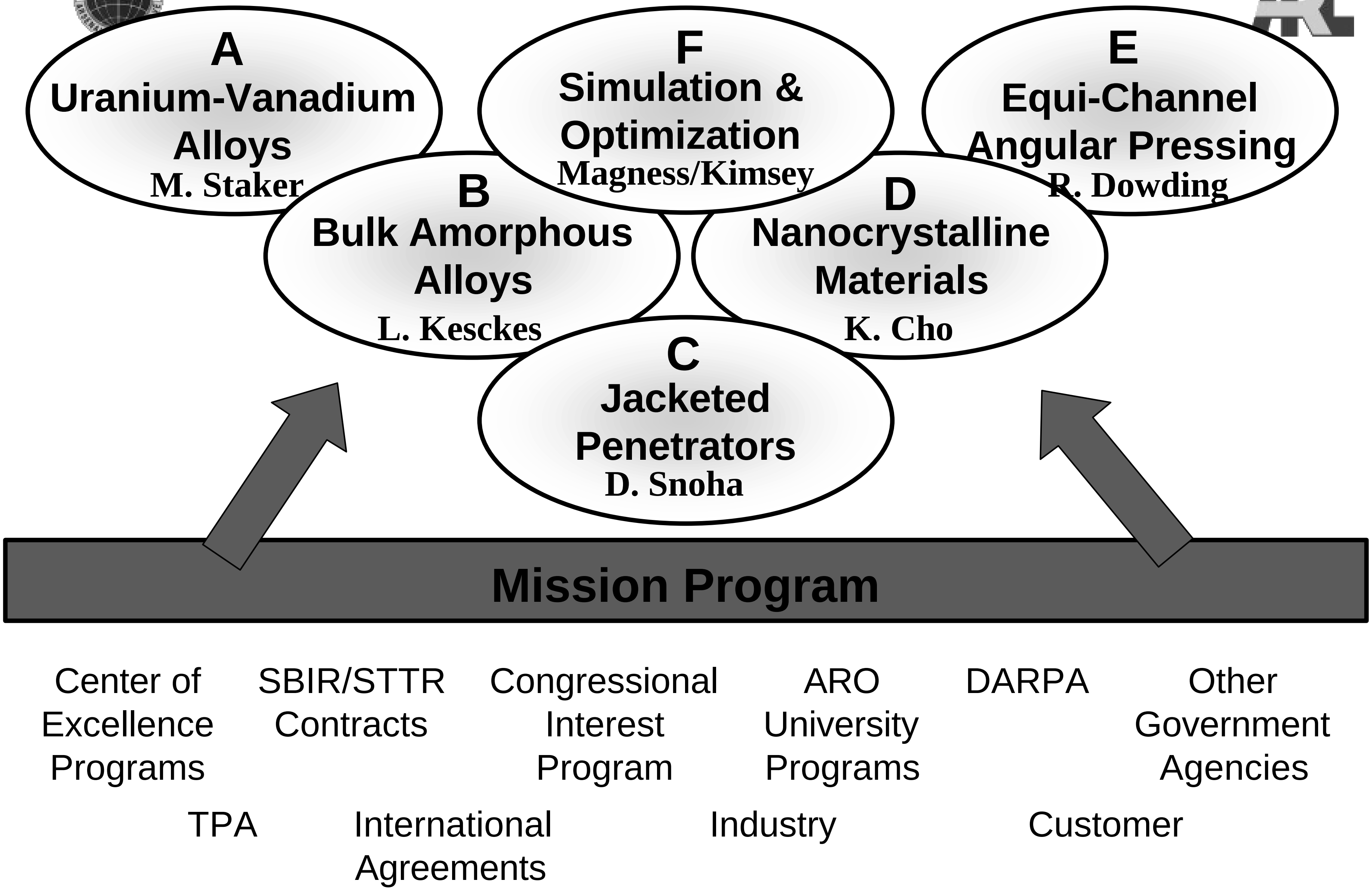


Deep Penetration performance is a function of alloy density & strain to shear failure.

Material Options

- **DU alloys**: Enhance susceptibility to shear failure, while retaining/improving engineering properties.
- **Non-DU materials**: change flow/failure behavior
  - – Use alternative matrices, selection based on mechanical <u>and thermal</u> properties that promote high-rate <u>(adiabatic)</u> plastic instability and localization
    - Matrix alloys w/high strength, low work hardening, low strain rate sensitivity, rapid thermal softening
  - – Amorphous & nanocrystalline materials as a candidate matrix alloy or entire composite (nano W phase)
    - exhibit localized shear failure in dynamic <u>and quasi-static</u> tests
  - – Anisotropic flow/failure of W crystals
- **Jacketed Penetrators**: Systems approach, with materials issues

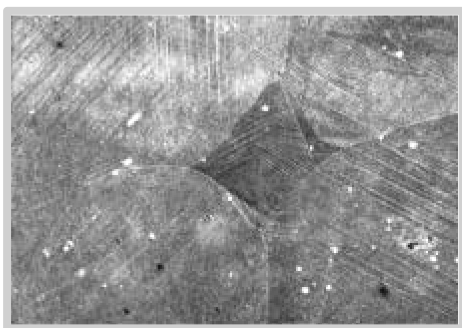
CURRENT ANTI-ARMOR MATERIALS DEVELOPMENT PROGRAMS

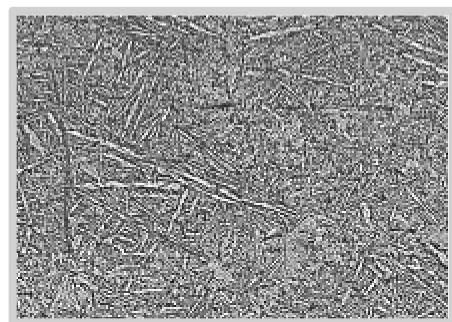


Uranium-Vanadium Alloys

Composition	Density	Hardness	Ult. Tensile Strength
	(g/cc)	HRC	(Ksi/Mpa)
U-V (1-4.5%)	16.7–18.5	36-54	To 310/2140
U-V-X(ternary)	16-18.5	36-55	To 320/2200
U-3/4Ti	18.6	38-49	To 250/1720

U-2.1%V, banded martensite (from Staker)

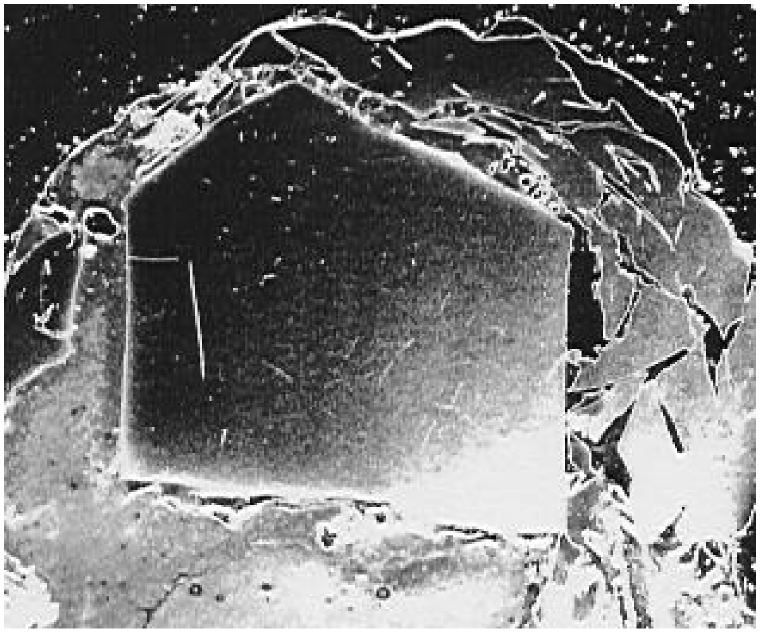




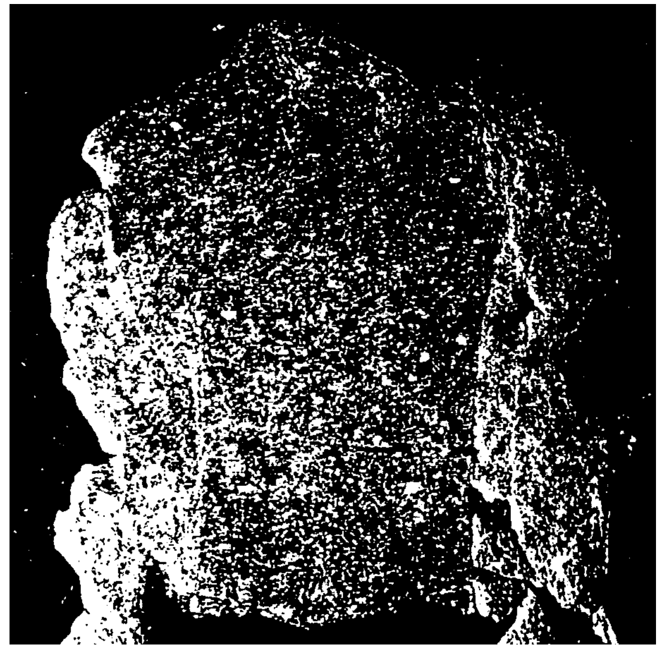
U-.75%Ti, acicular martensite (from Staker)

• U-V alloys have the potential to maintain penetration capability while reducing penetrator density and mass.

Tungsten Composites with Adiabatic Shearing Matrix Alloys



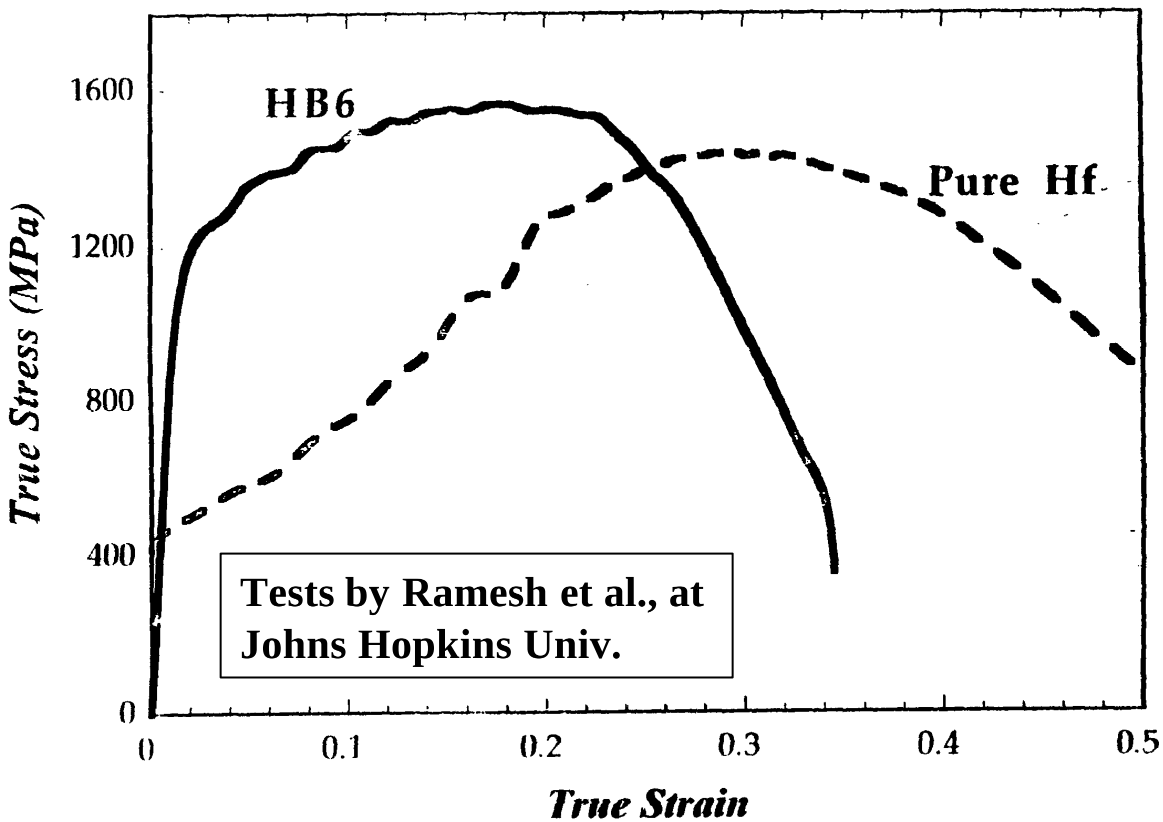
Residual Ti6Al4V Penetrator

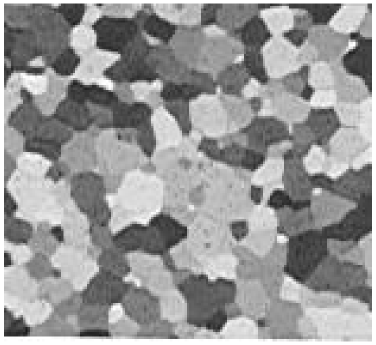


Residual W-Ti alloy Composite Penetrator

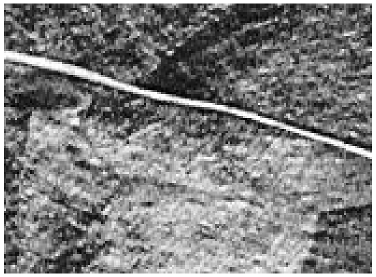
- Replace conventional Ni-Fe matrix alloy with one more prone to adiabatic shear failure, to enhance plastic instability.

Dynamic Compression Tests of Hafnium and Hafnium Alloy





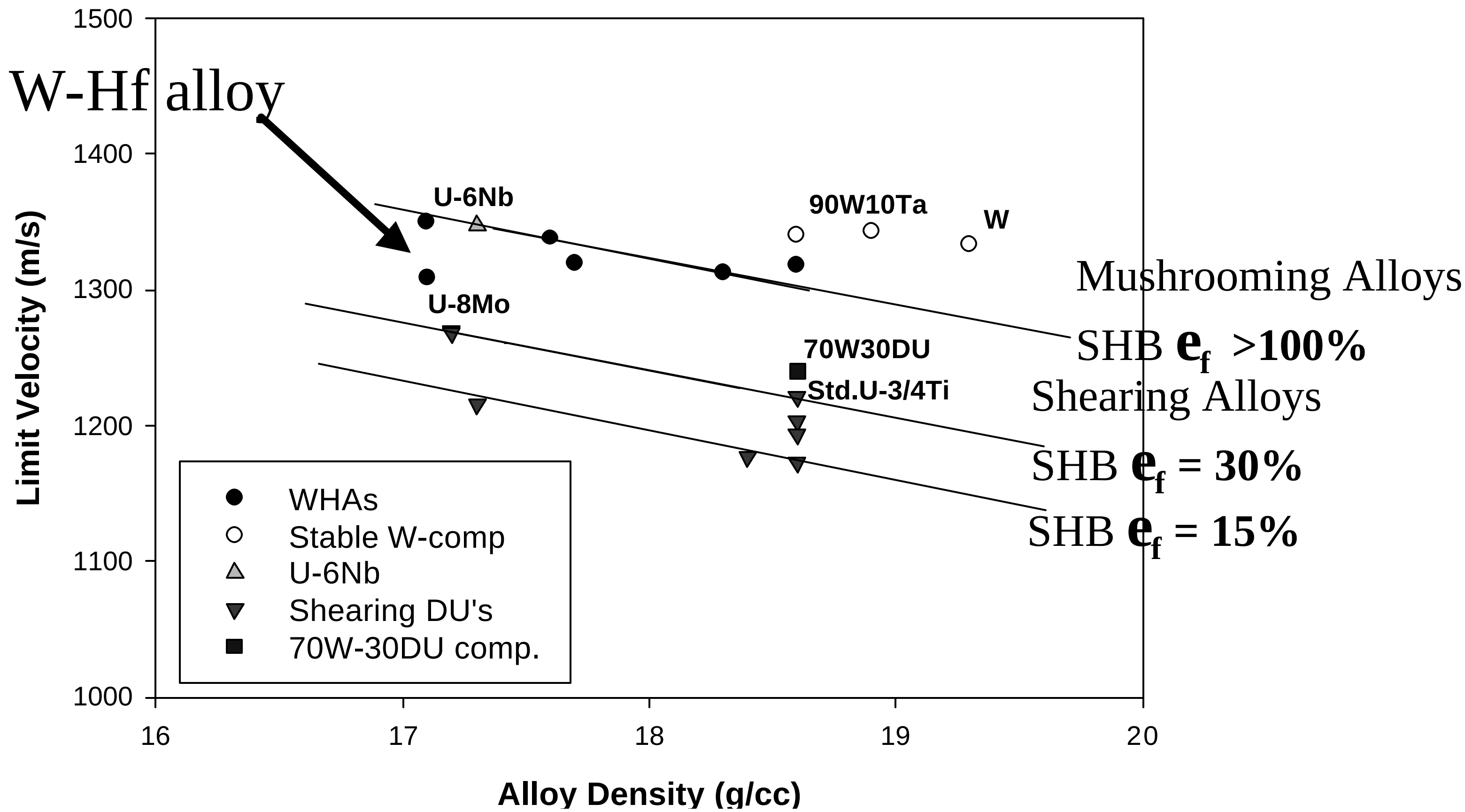
Unalloyed Hf



HB6, Hf10Ti10Ta

- Hafnium alloy HB6 demonstrated the preferred failure behavior in dynamic compression tests.

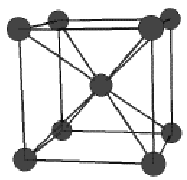
Perforation of Steel



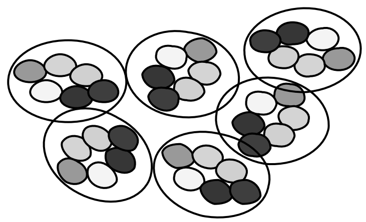
Performance of W composite with hafnium alloy matrix significantly better than conventional (Ni-Fe)-matrix WHAs, but still short of DU.

W Composites with Bulk Amorphous Metal (BAM) Matrices

- Amorphous alloys lack long-range structure of crystalline solids.



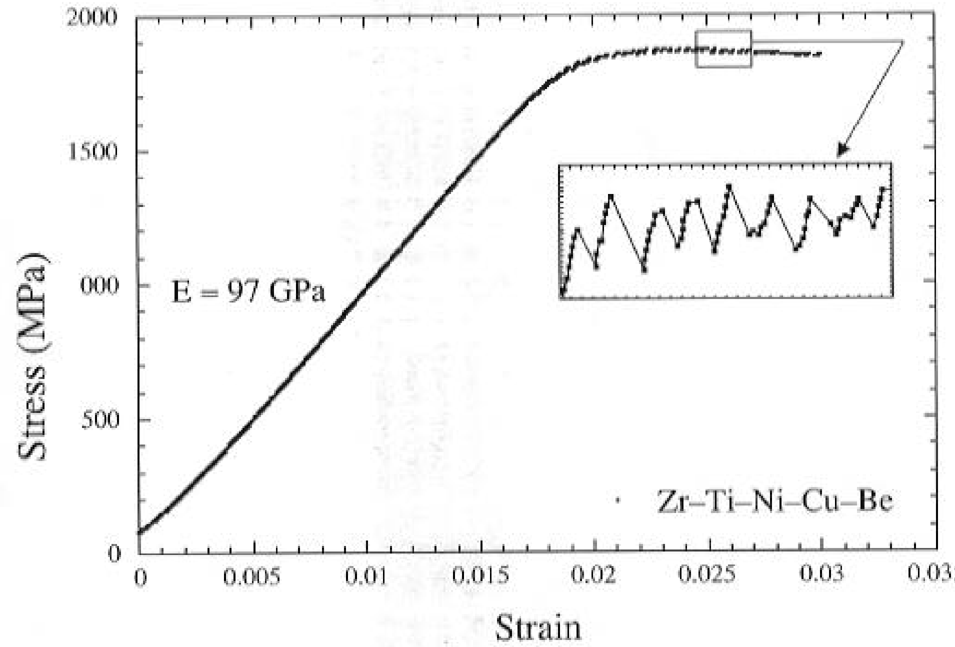
Crystalline

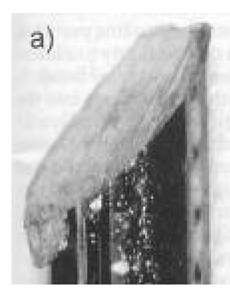


Amorphous

- Unique mechanical properties: high elastic limit (2-3% strain, 1.6GPa Y.S., no work-hardening).
- Recent development of complex, multi-component bulk metallic glass alloys make 1 to 5 cm thick sections possible (low quench rates)

Typical Mechanical Behavior: no strain hardening in quasi-static s-e curve, serrated plastic flow (shear banding)



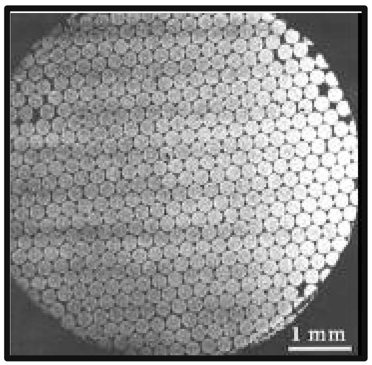


Angled (~ 45°) shear band failure

“Deformation Mechanisms of the ZrTiNiCuBe Metallic Glass”, Wright, Saha, & Nix

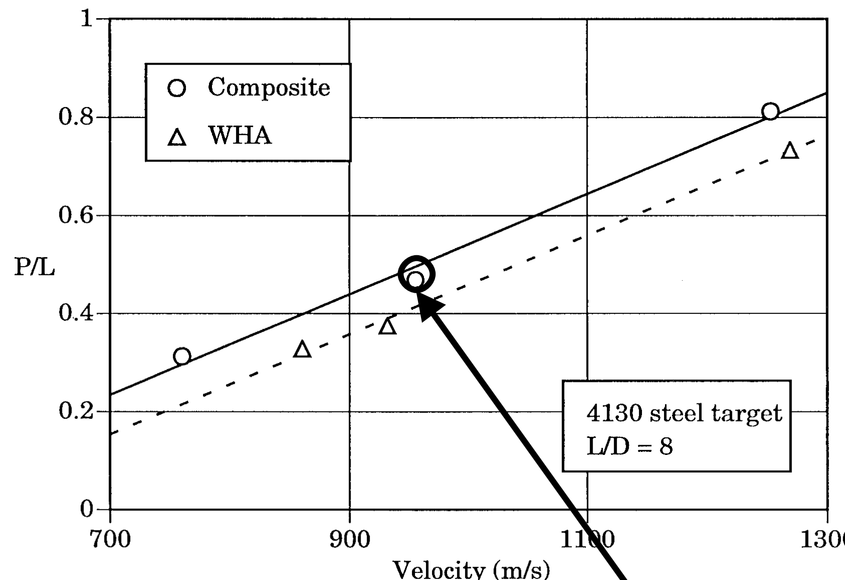
W Composites with Bulk Amorphous Metal (BAM) Matrices

- ARO-funded CalTech development of W-composite using Z-Ti-Cu-Ni-Be bulk castable amorphous alloy

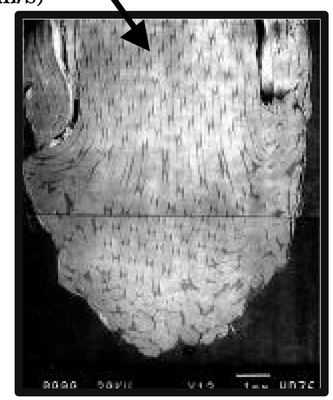


Tungsten wire/ amorphous alloy composite.

80% wire reinforced.

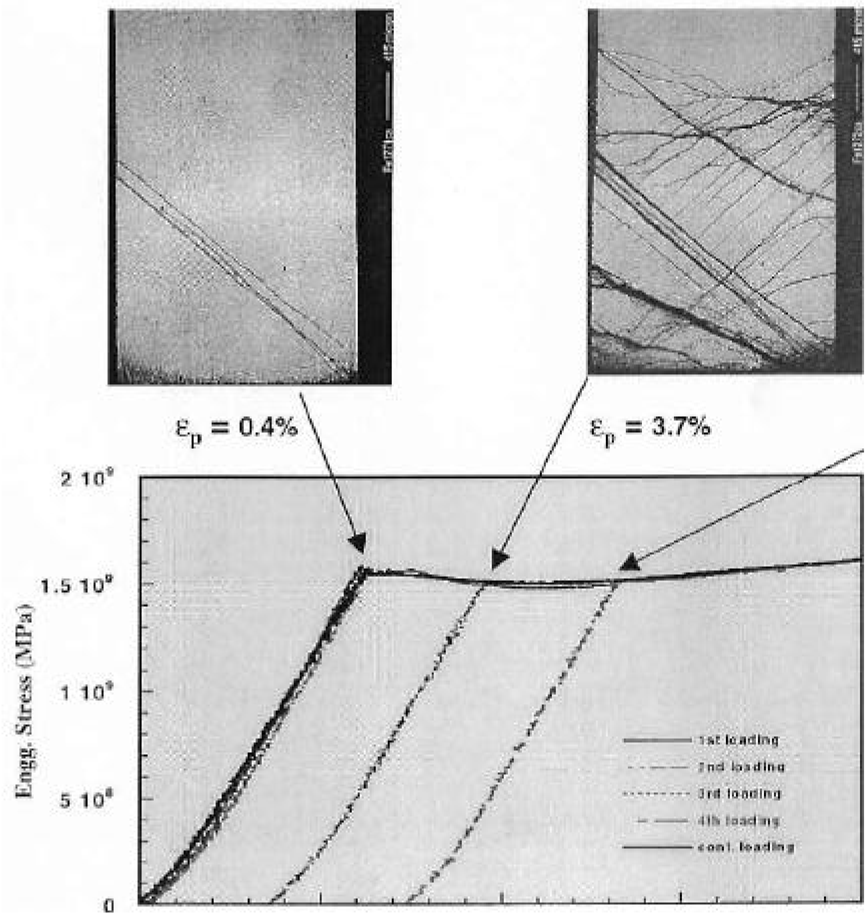


Sub-scale ballistic tests suggest DU-like improvement in penetration performance. From ARO grant to CalTech (W. Johnson)



Nanocrystalline Materials

- Like amorphous metals, nanocrystalline (<100 nm GS) metals exhibit little or no work-hardening or bulk plasticity in quasi-static tests
- Shear banding behavior has been observed in materials with GS >250 nm

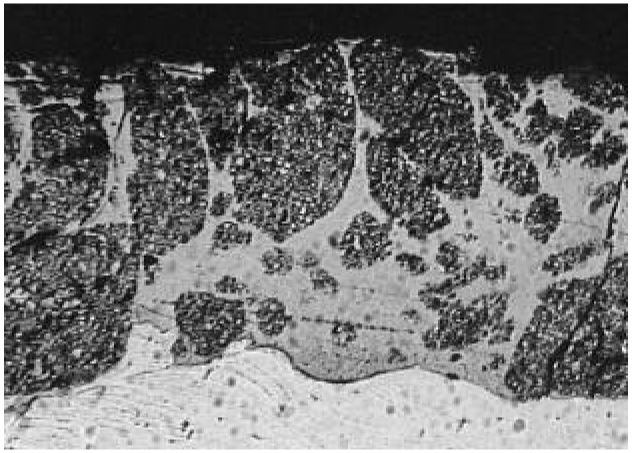


Tests by Dexin Jia, of Johns Hopkins U., aver.GS 268 nm

Ballistic Tests of Nanocrystalline W-Composite

Penetrator Type	Material	Density	Limit Velocity
		(kg/m^3)	(m/s)
Depleted Uranium	U-3/4 Ti, Rc 40	18600	1260
Conventional WHA	90W-9Ni-1Co	17100	1390
Nano W-Composite	W-Cu-Ni-Al	15200	1347
W-Composite w/Hf matrix	80W-20 HB3	17000	1350

- Performance of nanocomposite surpassed that of conventional WHA or best adiabatic-shearing matrix, despite lower density
- DU vs. WHA performances narrowed, but DU is still superior



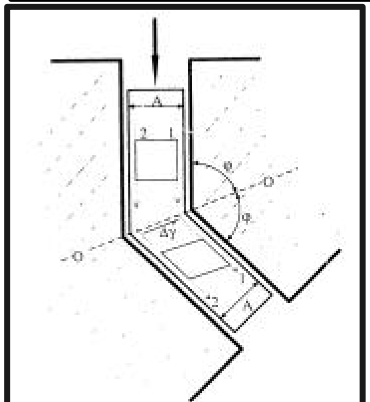
Nano W-Composite Penetrator Erosion Products Lining Penetrator Tunnel (15X)

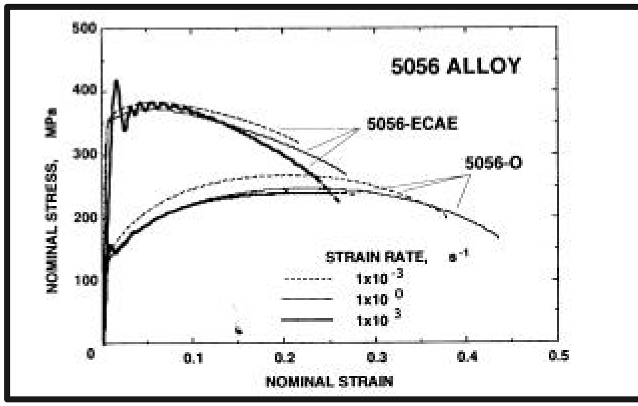
SEVERE PLASTIC DEFORMATION PROCESSING

Equi-Channel Angular Pressing (ECAP)

- New Mechanical Working Technique
- Developed in FSU

•Path to improved mechanical properties or alternative path to grain size refinement (nano)





5056 Aluminum Alloy
ECAE, >2x strength

Key Features

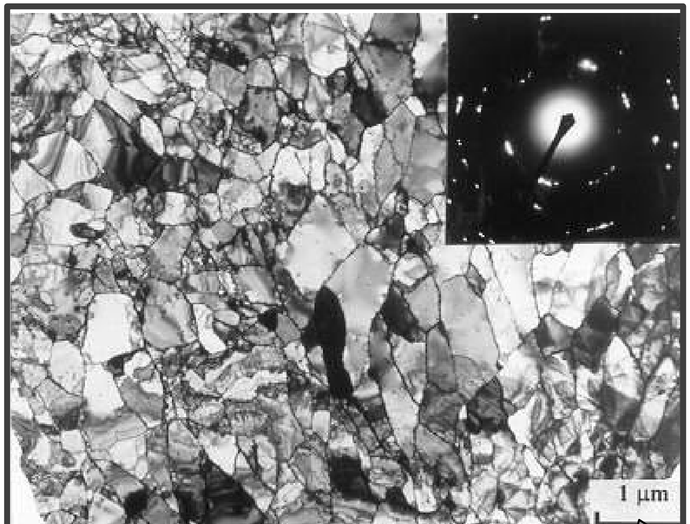
- Cross section in equals cross section out.
- Pure shear deformation
- Imparts cold work (>99%) with or w/o microstructural changes (reversible).

•Multiple passes increase deformation, refine grain size

#0f Passes	Equiv. Reduction
1	69%
2	90
4	99
8	99.99

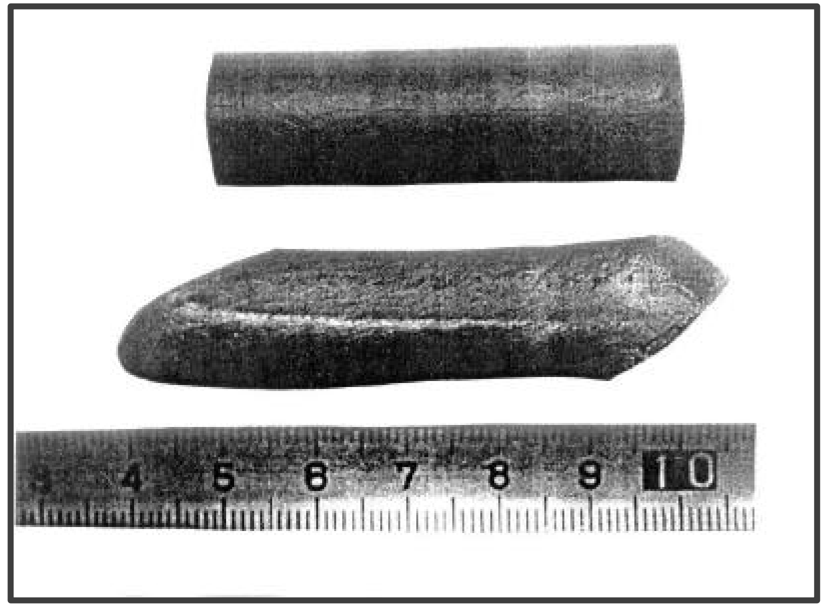
PARTICULATE MATERIALS
PMPT
PROCESSING TEAM

TEM STRUCTURE AND MICRODIFFRACTION PATTERN 8 PASSES, ROUTE C



Cross Section

1 μm



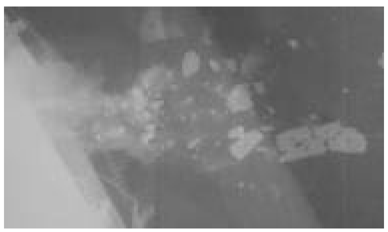
Die Angle of 110°
Route C, 4 Passes

- Ultra Fine Grained (UFG) Structure
- Mean Grain Size Approximately 1 μm, many grains 0.3 to 0.5 μm

PARTICULATE MATERIALS
PMPT
PROCESSING TEAM

Material Bonding for Jacketed Penetrators

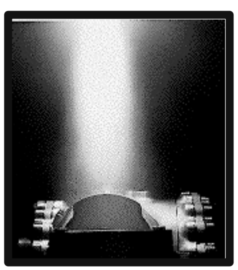
Goals: Fracture Resistance, Improved Stiffness, Reduced Mass



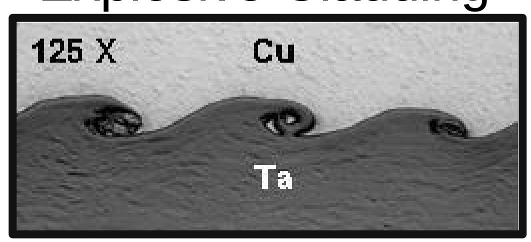
Jacket Material Selection and Bond Strength will be Key to success

Candidate bonding techniques guided by ballistic experiments and simulations; FOCUS – High Strength Bonds

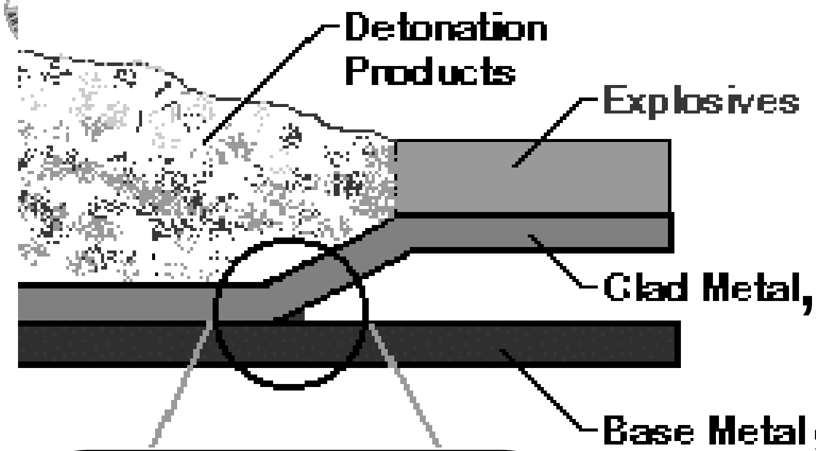
Thermal Spray



Explosive Cladding



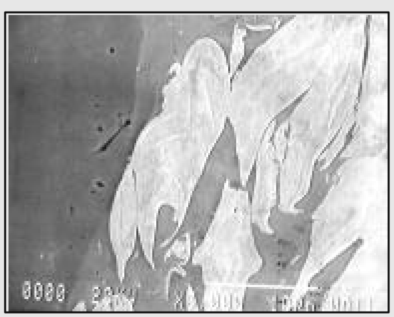
Material Bonding for Jacketed Penetrators



, 316L Stainless Steel

, Tungsten Heavy Alloy

✓Metallography
✓Centerline Properties
✓ High Strength Bond



- High Strength Bond Achieved!
  - Subscale Experiments Pending
  - Reactive & Passive Targets
- Follow-on contract in place.
  - Full Scale Processing
- Iterate based on Ballistic Results.
- Future – Consider alternate bonding.
  - Swaging
  - Co-extrusion
  - Cold Spray

Conclusions/Summary

- Certain minimum mechanical properties required for launch, for performance vs. complex armors
- Efficient flow & failure behaviors improve penetration performance against thick monolithic armor <u>and</u> individual armor components (e.g. basal armor behind ERA applique)
- Alloy development efforts must meet both goals